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THE VELOCITIES OF THE STARS

By GUSTAF STROMBERG

Our knowledge of the motions of the stars was for a long time based exclusively on the proper motions, which were obtained by comparing the positions of the stars at different epochs. Later our knowledge of their velocities was augmented by the spectroscopic determinations of radial velocities, which give us the motion in the line joining the Sun and the star. The large number of accurately determined parallaxes for individual stars recently secured by the study of stellar spectra has made it possible to convert the proper (angular) motions into linear measure (kilometers per second). By combining this velocity with that in the line of sight the true motion of a star relative to the Sun can be computed. There are thus three different methods of studying the motions of the stars, viz., those based upon proper motions, radial motions, and total or space motions. A short account of the results of investigations along these three different lines will here be given.

As the Sun is presumably moving among the stars we can attribute a part of the motions of the stars relative to the Sun to a motion of the Sun itself. As we do not have any fixed system of reference, we must decide more or less arbitrarily upon one convenient for our purpose. The simplest way, and that commonly used, is to start from the center of gravity of a large number of stars and use this as our reference system. Not knowing the individual masses of the stars, we have to assign them all the same mass. It has been shown that the Sun's velocity relative to the center of mass of different groups of stars comes out very nearly the same, provided the groups contain a sufficiently large number of stars. This indicates that this center of gravity, or centroid, as it is called, can be used as a convenient system of reference.

Referring the velocity of a star to this centroid can thus be regarded as equivalent to assuming our stellar system to be at rest in space. The velocity of a star relative to the centroid is called the star's peculiar velocity. A study of the motions of

the stars is thus generally divided into two parts, a determination of the Sun's velocity on the one hand and a determination of the distribution of the peculiar motions on the other.

The Sun's motion was first determined by Sir William Herschel in 1783 from the proper motions of only seven stars, yet the determination gave a fairly good first approximation. Since that time the number of stars whose proper motions are well determined has been vastly increased. The most accurate proper motions available at present are collected in Boss's *Preliminary General Catalogue of 6188 Stars*, and from these Boss has found that the Sun moves towards a point in right ascension 270° and declination $+34^\circ$. From the radial motions determined at the Lick Observatory and the D. O. Mills Observatory, Campbell has found that the Sun moves with a velocity of 19.5 km per second towards a point in right ascension 268° and declination $+25^\circ$. The point in the sky towards which the Sun is moving is called the Sun's apex, and according to the numbers just given lies between the constellations of Lyra and Hercules.

Later investigations seem to indicate that the fainter stars give a somewhat higher declination of the Sun's apex than the brighter stars, and furthermore that stars of spectral types K and M give higher declination than stars of earlier spectral type. A study of the space velocities recently made at the Mount Wilson Observatory shows that the Sun's velocity comes out differently according as it is referred to giant or dwarf stars. Eight hundred giant stars give a solar motion of 18.8 km towards the apex $\alpha=273^\circ$, $\delta=+37^\circ$, and 415 dwarfs a velocity of 31.7 km towards the apex $\alpha=281^\circ$, $\delta=+30^\circ$. Another result of the study of the space velocities is that the speed of the Sun comes out very much greater if the determination is based upon stars which themselves have high speed, indicating that the speedier stars do not move with equal frequency in all directions, but tend to favor a direction nearly opposite that in which the Sun is moving.

As the stars are moving in all directions and with different speeds, an important question is to find out how many stars are moving in one direction as compared with the number mov-

ing in another direction, and how the average speed of the stars varies with the direction of motion. In order to answer this question we must determine the law of the distribution of velocities according to speed and direction of motion. Using a standard solar velocity of 20 km towards the apex $\alpha = 270^\circ$, $\delta = +30^\circ$, we can obtain a system of reference relative to which the peculiar motions of the stars can conveniently be studied. In the earlier investigations it was generally assumed that the peculiar motions of the stars were distributed at random. In 1904, however, Kapteyn showed that such an assumption could not be upheld, and pointed out that the distribution of proper motions could be explained by assuming that the stars were mainly moving in two opposite directions, thus constituting two star streams. These two streams seem to be entirely intermingled in space and can be traced among stars at all distances. If the study is based upon proper motions, which necessarily are measured relatively to the Sun, the two star streams form an angle of 100° with one another. If we consider one stream to be at rest, the velocity of the other referred to it is 39 km in the direction of the galactic longitude 168° , and lies very nearly in the galactic plane. This indicates that the majority of stars are moving parallel to a certain line in the galactic plane. This line evidently must be a very fundamental and important axis in the distribution of stellar motions.

Schwarzschild has pointed out that there is an alternative theory that will account just as well as the two-stream theory of Kapteyn for the observed distribution of stellar velocities. The "ellipsoidal" theory of Schwarzschild asserts that there is an axis along which the stars show a tendency to move and that the number of stars moving in other directions decreases regularly as the angle between their direction of motion and that of the preferential axis increases from 0° to 90° . The two-stream theory implies, in a certain sense, a dualistic conception of the stellar universe, while the ellipsoidal theory asserts that the occurrence of large peculiar velocities is most frequent if the direction of motion is along a certain line, while it is least frequent if the direction is perpendicular to this line.

If we study different classes of stars, however, we find that

the distribution of velocities is not the same for different spectral classes and different intrinsic brightness of the stars studied. Campbell and Kapteyn found that stars of the later spectral types move faster than the stars of the earlier types, stars of spectral class B having the smallest velocity. This was confirmed later, but in addition it was found that for stars of the same spectral class the absolutely fainter stars in general had a considerably higher velocity than stars of greater intrinsic brightness. Furthermore the B stars had a tendency to move in all directions in the galactic plane instead of along one axis in this plane.

The stream-motion is most pronounced among the A and F stars and somewhat less so among the G and early K stars, while the later K stars and the M stars show hardly any stream motion at all, all directions of motion occurring with nearly the same frequency.

The question as to whether the two-drift theory or the ellipsoidal theory is best suited to represent the observations is difficult to settle when dealing with proper motions or radial velocities separately. If accurate distances of a large number of stars were known, it would be a simple problem to compute the three velocity-components for the individual stars, and to settle the question. On account of their smallness most trigonometric parallaxes are not accurate enough for this purpose, although they furnish us with a mean, by which parallaxes determined in a more indirect way can be calibrated. The spectroscopic parallaxes are well adapted for this purpose, as their errors are proportional to the parallaxes themselves and thus are very small for the smaller parallaxes.

A computation of the three velocity components for about 1300 stars of spectral types F to M, made recently at the Mount Wilson Observatory and already alluded to in connection with the solar motion may contribute to the solution of this question. To fix our ideas let us think of a number of stars starting at the same instant from the same point and let them move for one second with velocities equal to and parallel to their observed velocities in space. They will then have spread out into a cluster, and the study of the distribution of the real

velocities is identical with the study of the distribution of the stars in this velocity-cluster. To simplify matters and make possible a mathematical treatment of the problem, we replace this cluster by a body, the density of which changes continually from point to point and is equal to the number of stars per unit of volume in the cluster. If all the stars moved at random in all directions, the "velocity-cluster" would be globular with a condensation-point in the center, and the "velocity-body" would be comparable with a spherical mass of gas, the density of which would decrease from the center outwards equally in all directions according to some law. The surfaces of equal density (equi-frequential surfaces) are in this case concentric spheres. According to the two-stream theory there are two condensation-points, one corresponding to each stream, and the equi-frequential surfaces either surround these points separately or, for the lower densities, surround them both. According to the ellipsoidal theory the equi-frequential surfaces are concentric ellipsoids, whose major axes coincide with the axis of preferential motion.

The study of the space velocities indicates that the velocities of the F stars actually are distributed nearly in accordance with the two-stream theory, and that one of these streams can be identified with the Taurus stream. The Taurus "stream" or "group" is constituted of a number of stars in the constellation of Taurus whose motions are almost exactly parallel to one another. There seems thus to be a fairly large number of stars of F type in all parts of the sky whose motions are nearly equal and parallel to that of the stars belonging to the Taurus group. The other condensation-point which may be identified with the second stream is the center of another distribution of velocities, which in itself is ellipsoidal, the major axis having a galactic longitude of about 0° and thus nearly coinciding with the x-axis in Fig. 1. If we study the brighter F stars and the brighter stars of spectral type G0 to G5, we find that they contain only a few stars of this general Taurus stream, while the majority of these stars form a group with an ellipsoidal distribution of velocities. The curves of equal frequency given in Fig. 2

are the intersections of the equi-frequential surfaces with the galactic (xy) plane and with a plane through the x- and z-axes, the latter being directed towards the pole of the galaxy.

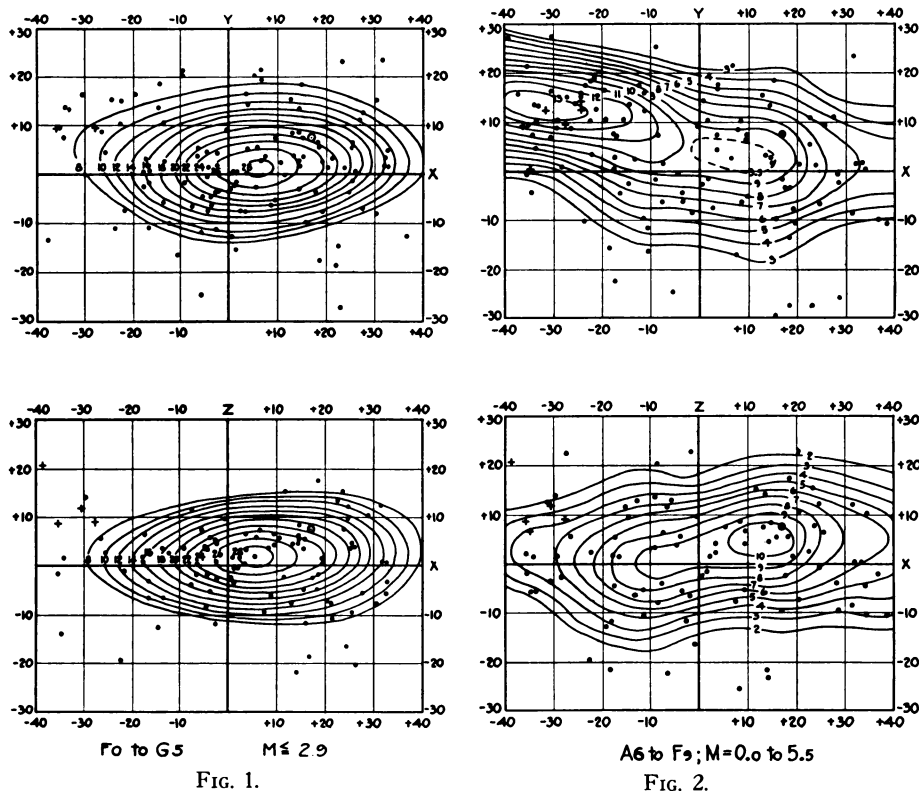


FIG. 1. Diagrams showing the motions of the brighter stars of Classes F and G.

FIG. 2. Diagrams showing the motions of the fainter stars of Class F.

For the giant stars of the later types we find a distribution of velocities similar to that of the brighter F and G stars, but with a larger spread and less elongation of the ellipsoids. For the later K and M stars the distribution is nearly spherical, but the condensation-point is the same as that for other giant stars.

The dwarf stars seem to form a group of their own as far

as their motions are concerned. The distribution of the velocities is ellipsoidal, but the most frequent velocity is quite different from that derived for giant stars. This velocity relative to the Sun is 37.7 km in the direction $\alpha=99^\circ$, $\delta=-17^\circ$, while for the giant stars it is found to be 13.4 km in the direction $\alpha=86^\circ$, $\delta=-31^\circ$. Taking the opposite points in the sky we find that these vectors do not agree with the velocities of the Sun as based upon giant and dwarf stars. The reason for the discrepancy has been found to be an asymmetry in the distribution of the velocities produced by a tendency of the stars of high velocity to avoid moving toward that part in the sky between the constellations Aquila and Cassiopeia. Not a single star having a space velocity of more than 100 km per sec is moving in this general direction. This peculiar distribution of the motions of stars of high velocity was first discovered by Adams and Joy from a study of a few stars of high radial velocity, but is now found to be a general feature of the stars of high velocity. This asymmetry has been found to exist in a less degree even among stars of ordinary speed, and is the reason why in Figs. 1 and 2 the condensation-point of the velocity distribution does not coincide with the origin.